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SEE AND AVOID SENSOR SYSTEM DESIGN PART II - SYSTEM RELIABILITY & COST/BENEFITS

Won-Zon Chen
Eric Portilla
Bruce Clough
Thomas J. Molnar

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AIR FORCE MATERIEL COMMAND
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Won-Zon Chen and Eric Portilla (Northrop Grumman Integrated Systems)
Bruce Clough and Thomas J. Molnar (AFRL/VACC)

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MS 9L40/W6
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Authors: Won-Zon Chen, Eric Portilla
Northrop Grumman Integrated Systems
MS 9L40/W6
El Segundo, CA 90245-2804
Tel: (310) 332-7257
E-mail: chenwo@mail.northgrum.com

Bruce Clough, Thomas J. Molnar
AFRL/VACC B45 Rm 270
WPAFB, OH 45433-7542
Tel: (937) 255-8439
E-mail: thomas.molnar@wpafb.af.mil

***Abstract*:**

Under the USAF-sponsored Autonomous Flight Control Sensing Technologies (AFCST) program, Northrop Grumman investigated "see and avoid" (S&A) sensing requirements and preferred system designs along with other military scenarios such as autonomous formation flight and visual landing for future advanced unmanned air vehicles (UAVs). In the first part of the two-paper series, an S&A sensor coverage assessment method and the associated field-of-view (FOV) and time-to-go (TTG) modeling tools developed are described. In this second part, the use of the coverage models and modeling results to assess the overall system reliability of a number of sensor system configurations and their cost/benefit trades are discussed.

I. INTRODUCTION

To operate UAVs in FAA-controlled airspace, one must demonstrate a "level of safety equivalent to that of manned systems" if not better. Midair collision (MAC) has been a threat to manned systems, particularly around airport areas containing the greatest traffic concentrations. FAA statistics show a total of 152 MACs from 1978 to 1982 in the United States resulting in 377 fatalities. During the same period, 2,241 near midair collisions (NMAC) were reported [1],[2]. One can easily understand that this problem

can get more severe for UAVs if provisions are not provided to substitute for pilot's vision, the so called "see and avoid" (S&A) problem.

Under the USAF-sponsored Autonomous Flight Control Sensing Technologies (AFCST) program, Northrop Grumman is developing sensing requirements and preferred system designs for autonomous UAV airspace operation [3], [4]. This is the second part of a two-paper series. In the first part an S&A sensor coverage assessment method and the associated field-of-view (FOV) and time-to-go (TTG) modeling tools developed are described. In this second part, the use of the coverage models and modeling results to assess the overall system reliability of a number of sensor system configurations and their cost/benefit trades are discussed.

As discussed in the first part of the paper, S&A sensing capability can be greatly impacted by atmospheric conditions, intruder's speed and size or signature, collision angles, etc. A perfect sensor system would then have to have a spherical 4-pi coverage with an extended detection range in all weather conditions. Moreover, it must incorporate redundant components in case something fails. Such a system could not only be expensive, but also unnecessary. Hence, the motivation for this study was to: 1) develop an S&A sensor system reliability analysis method, 2) develop tools to facilitate the reliability analysis, 3) obtain insights to sensor cost/benefits trade, and 4) the results used to facilitate S&A requirements specification and tailoring. Figure 1 gives a pictorial description of these study objectives and data flow.

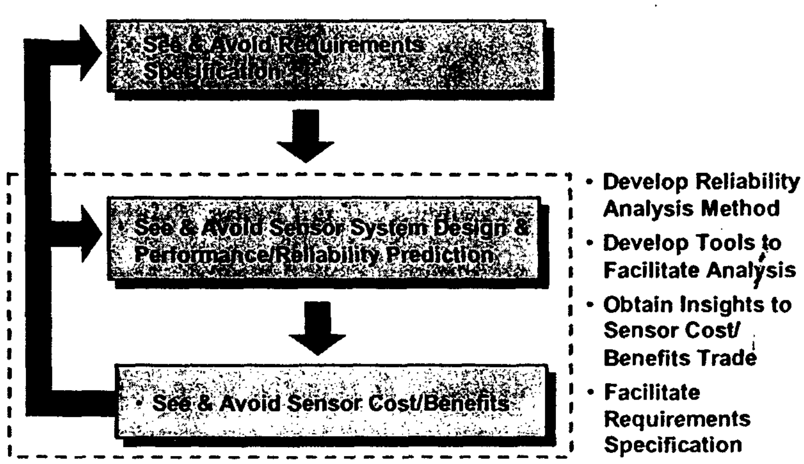


Figure 1 S&A Sensor System Reliability Analysis Objectives

In Section II, S&A sensor system reliability definition and analysis method are described. Vehicle operating conditions and seven sensor configurations used in this study are described in Section III. The reliability analysis results in terms of cost versus benefits for a landing condition (i.e., low altitude and low closing speed) and a cruise condition (i.e., high altitude and high closing speed) are given in Sections IV and V, respectively. The paper concludes with a brief summary in Section VI.

II. RELIABILITY ANALYSIS APPROACH

Before plunging into S&A sensor system reliability, we must determine what has to go wrong for a MAC or NMAC (defined as an intruder flown by within 500 feet) to occur. Figure 2 shows a top-level MAC/NMAC fault tree. First, the intruder can be detected and avoided either with S&A sensors or with collaborative systems such as Traffic Alert & Collision Avoidance System (TCAS). This point is denoted in the bottom left of the fault tree in Figure 2 by using an AND gate to combine the probability of "Fail to See in Time" and "Fail to Detect in Time." However, sensor data must be processed in order to generate detection, alert, and subsequent avoidance maneuver commands. This could not be done properly in the presence of critical processing (including software) or data bus failures. This explains why an OR gate is used to combine the probability of "sensor failures" with "processing/data bus failures" in the middle of the fault tree. Finally, for a MAC or NMAC to occur the intruder must be on a collision course with the ownship to begin with, which means air traffic management (ATM) rules are broken either by the intruder, the air traffic controller (ATC), or the ownship. A study of FAA mishap statistics confirmed that the history of these occurrences is as low as 5 x 10**-6 per departure. This reasoning is represented by an AND gate at the center top of the fault tree. A word of caution here – past rates not to predict future trends. With future skies becoming more crowded and less centrally regulated the chances of collision could increase, thus using past occurrence rate could give a false impression of security.

Within the aforementioned overall MAC/NMAC picture, this paper only addresses the S&A sensing portion of the overall problem as highlighted in Figure 2. Based on this definition, one could interpret the S&A sensor system reliability as: given you are on a collision course with an intruder, the processing hardware/software is fine, but no TCAS,

what then is the probability of seeing and avoiding the intruder? With this clarification let's now examine the S&A sensor system reliability assessment method.

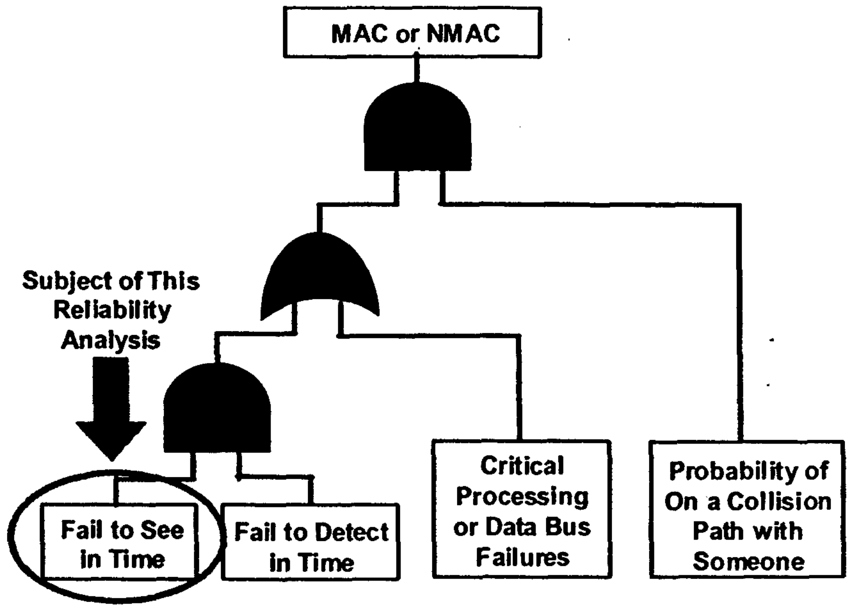


Figure 2 <u>**Top-Level MAC/NMAC Fault Tree**</u>

To calculate S&A sensor system reliability, one must consider all three aspects: 1) not being able to see (i.e., not enough sensor FOV), 2) not seeing it far enough (i.e., not enough TTG or sensor detection range), and 3) sensor not available (i.e., sensor failures). The first two aspects are grouped as sensor coverage, denoted by C, which is the subject of the first part of the paper. In this paper, we include the effect of the third aspect, sensor availability denoted by A. Note that A is a function of sensor failure rate and mission duration. For instance, for a mission of T hours and a sensor mean time between failures (MTBF) of X hours, the sensor availability A can be approximated as A = 1 – (T/X). Hence, the reliability of an S&A sensor can be further approximated as R = A * C.

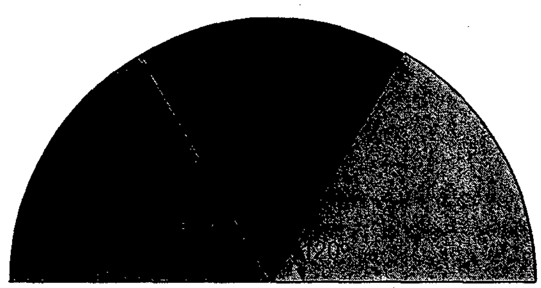
While the formula above is rather straightforward for a single sensor, this can become complicated for multi-sensor configurations of dissimilar and/or overlapping sensors. For example, two vision sensors may be incorporated with FOV overlaps to provide redundancy and some stereo ranging capability. This pair of vision sensors may be further complemented with a forward-looking radar to provide a better weather capability. For these multi-sensor configurations, it is important to understand that sensor

coverage can be spatially correlated, thus not additive. This phenomenon can be illustrated by a simple example in Figure 3 where two sensors each have a 120 degree FOV, overlapping 60 degrees. Note that the overall coverage of the two sensors is only 180 degrees or 0.5 (i.e., 180/360 = 0.5), but not the linear sum of 240 degrees or 0.66. Therefore, to calculate multi-sensor system reliability, the probability of sensor availability and sensor coverage must be evaluated for each combination individually (i.e., sensor #1 is OK, sensor #2 fails, etc.) and then the reliability for each sensor combination summed together for the overall system reliability as below.

$$R = \Sigma\ Ci * Ai$$

Specifically, for the example in Figure 3 its system reliability can be calculated as:

$$\begin{aligned} R &= \Sigma\ Ci * Ai \\ &= 0.5 * A_1 * A_2 \\ &\quad + 0.33 * A_1 * (1-A_2) \\ &\quad\quad + 0.33 * (1-A_1) * A_2 \end{aligned}$$



C1 = 0.33
C2 = 0.33
C1& C2 = 0.5 ≠ 0.33 + 0.33

Figure 3 **Combined Coverage/Reliability of Overlapped Sensors**

III. VEHICLE OPERATING CONDITIONS & SENSOR CONFIGURATIONS

Two vehicle operating conditions, a low-altitude, low-closing-speed landing condition and a high-altitude, high-closing-speed cruise condition, were chosen for the S&A sensor system reliability analysis as shown in Figure 4. The landing condition, called Case 1, was an obvious choice since this is where most MAC/NMAC occur. The ownship speed of 160 knots at 5K feet altitude was chosen to represent the High Altitude

Long Endurance (HALE) class of UAVs. Weather or visibility would be typical concerns at these low altitudes and hence a strong S&A sensor design driver. The relative low closing speed provides a relief factor from sensor detection range viewpoint for this case since the FAA limits airspeed to below 250 knots when operating below 10 Kft. Also note that below 10K feet is the primary operating zone for general aviation (GA) aircraft that may not be equipped with a TCAS. In this case, S&A sensor system would be the only protection when the ATM rules are somehow broken. Figure 4 also assumes a probability mix for intruder types (i.e., GA, small fighter (SF), and commercial transport (CT)) and for weather in terms of visibility and rain rate. It was further assumed that the intruder could approach from all horizontal directions in even probability. For the vertical plane, it was assumed that the relative flight path angle would be limited to within +/- 20 degrees in even probability. These assumptions are somewhat simplified, but believed to be a reasonable choice for a generic study.

- **Case 1** --- 160 knots @ 5k ft Alt (all A/C limited to 250 knots)
  - Threats
    - 30% GA 0.6 to 1.0 speed ratio +/- 20 deg relative γ
    - 10% SF 1.0 to 1.6 speed ratio +/- 20 deg relative γ
    - 60% CT 1.0 to 1.6 speed ratio +/- 20 deg relative γ
  - Weather
    - 50% 23nm visibility, no rain
    - 32% 10nm visibility, no rain
    - 14% 3nm visibility, no rain
    - 4% 0nm visibility, 4mm/hr rain
- **Case 2** --- 340 knots @ 30k ft Alt
  - Threats
    - 20% SF 1.0 to 1.6 speed ratio +/- 20 deg relative γ
    - 80% CT 1.0 to 1.6 speed ratio +/- 20 deg relative γ
  - Weather
    - 52% 23nm visibility, no rain
    - 33% 10nm visibility, no rain
    - 15% 3nm visibility, no rain

Figure 4 <u>**Assumptions for Two Vehicle Operating Conditions**</u>

Similarly, various assumptions were made for the high-altitude cruise condition called Case 2 in Figure 4. This case was purposely selected to complement the first case

of landing condition. The motivation was that at these high altitudes both the ownship and intruder are traveling at much greater speeds, thus significantly increasing the required S&A sensor detection range so that the ownship could have enough time to execute avoidance maneuvers. However, the compensating factors would be that weather is normally not as big a factor plus GA aircraft do not operate at these altitudes.

In addition to the aforementioned variations in vehicle operating conditions, a total of seven S&A sensor system configurations were also chosen as summarized in Figure 5. These seven sensor configurations span from a single MIDAS (Multifunction Infrared Distributed Aperture System) covering the limited frontal area to 6 MIDAS's and 5 KAMS's (Ka Multifunction Systems) that provide redundant 4-pi spherical coverage.

Sensor Configuration	MIDAS			KAMS			Normalized Cost per A/C
	Number per A/C	AZ FOV (deg)	EL FOV (deg)	Number per A/C	AZ FOV (deg)	EL FOV (deg)	
#1	1	+/-50	+/-50	0	0	0	1
#2	2	+/-100	+/-50	0	0	0	2
#3	2	+/-100	+/-50	1	+/-60	+/-60	4
#4	6	+/-180	+/-180	0	0	0	6
#5	6	+/-180	+/-180	1	+/-60	+/-60	8
#6	6	+/-180	+/-180	3	+/-180	+/-60	12
#7	6	+/-180	+/-180	5	+/-180	+/-180	16

Figure 5. <u>Sensor System Configurations & Normalized Cost</u>

MIDAS is a passive high performance cryogenetically cooled mid-wave IR sensor developed by Northrop Grumman under an ONR sponsored program. Each MIDAS has 1K x 1K detectors with a 100 degree by 100 degree instantaneous FOV. The KAMS, on the other hand, is an active Ka band (~ 33GHz) electronic-scan multi-mode radar. It has been developed with Northrop Grumman internal funds aimed at advanced UAV applications. For AFCST, a KAMS configuration of 2,330 radiators in a 0.57 square feet active area was chosen. KAMS, as configured, could scan +/- 60 degrees from boresight and provide a reliable detection of a small GA aircraft from 9nm away. This detection capability could be degraded to about 4nm at 4mm/hr light rain condition, but hardly

impacted by other weather elements such as fogs and clouds that would significantly impair the capability of EO/IR sensors (e.g., MIDAS).

The sensor configurations were chosen as follows: the sensor configuration #1 of 1 MIDAS in the front was selected for best affordability. In configuration #2, two MIDAS's were used to increase the horizontal FOV to +/- 100 degrees to mimic what a human pilot is capable of doing. A KAMS was then added to the 2 MIDAS's in configuration #3 to enhance intruder detection capability for low visibility conditions. In configuration #4, 6 MIDAS's were used to have a 4-pi spherical coverage. Then, 1, 3, and 5 KAMS's were added to the 6 MIDAS's in configurations #5, #6, and #7, respectively. The purpose was to have these KAMS sensors not only for better weather capability, but also for redundancy. Note that the MIDAS cost is normalized to 1 and KAMS cost is assumed to be twice of that of MIDAS.

IV. CASE 1: LOW-ALTITUDE LOW-SPEED LANDING CONDITION

The sensor coverage models developed under the AFCST program allow user-selectable success criteria. One such important success criteria would be sensor FOV responsibility. For example, if taken over by a faster intruder from behind is considered to be intruder's responsibility, the user can then set FOV success criteria to be forward hemisphere or sector (FS) only. However, if any collision is unacceptable, the user would then have to set FOV success criteria to be 4-pi or all aspect (AS).

Another important success criteria would be minimum TTG. The minimum TTG needed to execute evasion maneuvers and generate sufficient separation distance to the intruder largely depends on ownship's maneuverability and the desire to accomplish so without extremely aggressive maneuvers. For instance, TCAS invokes only milder vertical maneuvers to evade the intruders and thus the minimum TTG required is in the neighborhood of 35 to 43 seconds. However, if using more aggressive or maximum-g maneuvers is allowed, the minimum TTG can be easily reduced by several folds. This, of course, would vary from UAV to UAV due to their physical capabilities and/or operating policy.

To explore the sensitivity of the aforementioned aspects, four different success criteria were chosen: 1) all aspect responsibility with 43 second warning, 2) all aspect responsibility with 8 second warning, 3) forward sector only with 43 second warning, and 4) forward sector only with 8 second warning. Note that the longer 43 seconds was chosen to allow a TCAS-like gentle evasion maneuver [5]. The USAF is jointly developing with Sweden last-ditch aggressive maneuvers using the full aircraft physical capability under the Auto-Aircraft Collision Avoidance System (Auto-ACAS) program [6]. The shorter 8 seconds was chosen to represent such emergency escape option.

Figure 6 shows the reliability analysis results for sensor system configuration #1 – one MIDAS only. The analysis steps are briefly explained follow:

1. Begin with the success criteria of all aspect with 43 second warning. Use the coverage model to calculate sensor coverage for no failure condition first. This is repeated for each intruder type (i.e., GA, SF, and CT) and for each weather condition (i.e., 23nm, 10nm, 3 nm, and 0nm).
2. Roll up the coverage based on the assumed probability of occurrence previously shown in Figure 4. This would complete the first row in the first table in Figure 6. The bottom-line is that the overall sensor system coverage is 0.675803 (the last column of the first row).
3. The above 2 steps are repeated for the other three success criteria. At this point the first table is complete.
4. We now evaluate the effect of the probability of sensor failures in the second table. Since there is only one sensor, the situation is simple. There are only two combinations, the 1 MIDAS is either healthy or fails. An MTBCF of 12,076 hours and a 1-hour mission were assumed for this study. Note that the HALE class of UAVs can stay in air for days. The probability of encountering sensor failures will be increased proportionally to mission duration, and hence the impacts due to sensor failure rate will be more severe than the results shown in this paper.

5. Once the probability for each of the two combinations is calculated, the overall sensor system reliability can then be rolled up based on the formula described previously in Section II.

It's noted that the sensor system reliability of this configuration #1 is dominated by sensor coverage as opposed to sensor availability. This should not be too surprising since sensor coverage is only 0.675803 and yet sensor availability is much better at 0.9999.

No Failure

	TTG (sec)	GA					SF					CT					Total Average
		23nm	10nm	3nm	0nm	Avg.	23nm	10nm	3nm	0nm	Avg.	23nm	10nm	3nm	0nm	Avg.	
All Aspect	43	0.992	0.992	0.903	0.000	**0.940**	0.587	0.587	0.530	0.000	**0.556**	0.587	0.587	0.587	0.000	**0.564**	**0.675803**
Fwd Sector	43	0.992	0.992	0.903	0.000	**0.940**	0.655	0.655	0.597	0.069	**0.623**	0.655	0.655	0.655	0.069	**0.631**	**0.723121**

With Failures

	TTG (sec)	Pos	MIDAS			KAMS			MIDAS FOV		KAMS FOV		Total FOV		Probability	Total Av. Coverage	System Reliability	1 - System Reliability
			Frt	Bck	Top	Frt	Bck	Top	AZ	EL	AZ	EL	AZ	EL				
All Aspect	43	1	G	n/a	n/a	n/a	n/a	n/a	+/-50	+/-50	+/-0	+/-0	+/-50	+/-50	9.999E-01	6.758E-01	6.757E-01	3.243E-01
		1	F	n/a	n/a	n/a	n/a	n/a	+/-0	+/-0	+/-0	+/-0	+/-0	+/-0	7.874E-05	0.000E+00		
Fwd Sector	43														9.999E-01	7.231E-01	7.231E-01	2.769E-01

Figure 6. Sensor System Reliability – Configuration #1

Let's now look at the reliability analysis results for sensor configuration #2 in Figure 7. The steps 1 to 3 to build the table with no failure are the same as before. To build the table with failures becomes, however, more complicated. With two MIDAS's, there are a total of four combinations, namely both MIDAS's are healthy, one MIDAS is healthy but the other fails (two combinations), and both MIDAS's fail. The probability of occurrence and associated sensor system coverage was calculated for each combination as shown in the second table of Figure 7. These are then rolled up to the overall average like the previous case. Note that while the sensor coverage is improved significantly (e.g., from 0.675803 to 0.913635 for all aspect with 43 second warning), there is still little impact on sensor system reliability due to potential MIDAS failures. This actually would continue to be the case until sensor coverage becomes near perfect like configurations #6

and #7. For those cases, sensor failure rates would then become the limiting factor for sensor system reliability.

No Failure

	TTG (sec)	GA					SF					CT					Total Average
		23nm	10nm	3nm	0nm	Avg.	23nm	10nm	3nm	0nm	Avg.	23nm	10nm	3nm	0nm	Avg.	
All Aspect	43	1.000	1.000	0.911	0.000	**0.947**	0.938	0.938	0.885	0.000	**0.893**	0.938	0.938	0.938	0.000	**0.900**	**0.913635**
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.900	0.938	0.938	0.938	[illegible]	0.900	[illegible]
Fwd Sector	43	1.000	1.000	0.911	0.000	**0.947**	0.987	0.987	0.932	0.069	**0.943**	0.987	0.987	0.987	0.069	**0.950**	**0.948678**
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.069	0.950	0.987	0.987	0.987	0.069	0.950	0.953204

With Failures

	TTG (sec)	Pos	MIDAS			KAMS			MIDAS FOV		KAMS FOV		Total FOV		Probability	Total Av. Coverage	System Reliability	1 - System Reliability
			Frt	Bck	Top	Frt	Bck	Top	AZ	EL	AZ	EL	AZ	EL				
All Aspect	43	1	2G	n/a	n/a	n/a	n/a	n/a	+/-100	+/-50	+/-0	+/-0	+/-100	+/-50	9.998E-01	9.136E-01	9.136E-01	**8.644E-02**
		2	1B	n/a	n/a	n/a	n/a	n/a	0-100	+/-50	+/-0	+/-0	0-100	+/-50	1.575E-04	4.568E-01		
		1	2B	n/a	n/a	n/a	n/a	n/a	+/-0	+/-0	+/-0	+/-0	+/-0	+/-0	6.200E-09	0.000E+00		
															9.998E-01	9.181E-01	9.181E-01	8.195E-02
Fwd Sector	43														9.998E-01	9.487E-01	9.486E-01	**5.140E-02**
															9.998E-01	9.532E-01	9.531E-01	4.687E-02

Figure 7. Sensor System Reliability – Configuration #2

The reliability analyses for the remaining sensor system configurations were similarly performed except there were more sensor failure combinations and more tedious reliability calculations. Their details are skipped in this paper. For an overview of S&A sensor benefits versus cost, Figure 8 plots the overall reliability analysis results in the format of system unreliability (i.e., 1 – system reliability) versus normalized cost. The four curves represent the four different success criteria.

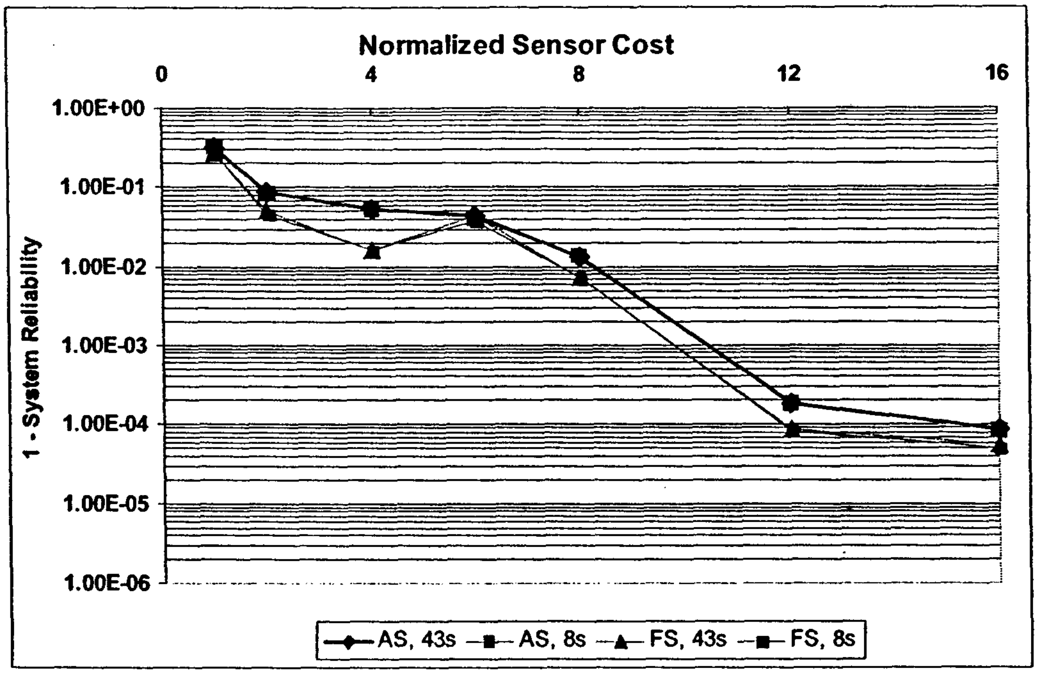


Figure 8. <u>Case 1 - Sensor System Reliability versus Normalized Sensor Cost</u>

From first glance at Figure 8, the relatively small reliability differences among the four different criteria are quite surprising, although the log scale tends to "de-amplify" the difference. With a careful study of the reliability analysis results of Case 1, the following interesting conclusions can be drawn:

- Configuration #1 - one MIDAS only could only cover a little more than one sixth of the 4-pi spherical surface, bur render a S&A sensor system reliability of about 0.65. It is debatable whether this configuration would be as safe as manned system from sensing viewpoint since its horizontal FOV is not as good as that of typical pilot out-of-window view, but it does have a better vertical FOV and a better detection range than human eyes [7].
- Configuration # 2 with 2 MIDAS's can bring the system reliability to about 0.91. Adding 1 KAMS (i.e., configuration #3) can further improve system reliability to about 0.95. In this case, it can be safely argued that both configurations would be safer than manned systems. The sensor cost for both configurations would also be not too excessive.

- Sensor cost would increase significantly in order to reach the level of 10**-4. Also, at this level sensor MTBF becomes a limiting factor. This means sensor reliability needs to be improved over beyond today's technology and this should be reflected in our government and industry investment strategy.
- Configuration #3 is more reliable than configuration #4. This indicates that if weather is a concern, it would be better off to add a forward-looking radar than adding additional MIDAS sensors for a 4-pi FOV.
- There is not much difference between 43 vs. 8 seconds TTG criteria because both MIDAS and KAMS are already sized to have a medium detection range of 3 to 10 nm. This would not be the case if lower performance sensors such as CCD's are considered.There is not much difference between all-aspect vs. forward-sector criteria. This is because none of the sensor configurations were chosen to optimize for just forward sector (i.e., +/- 90 degrees for both horizontal and vertical FOVs).

V. CASE 2: HIGH-ALTITUDE HIGH-SPEED CRUISE CONDITION

The sensor system reliability analysis was performed for Case 2 using the same method and tools described in the previous Section. The results are plotted in Figure 9 in the same format. Again, the reliability differences among the four different success criteria were not as big as expected, although the spread is wider than that of Case 1. Also, a careful study of the reliability analysis results in Figure 9 would yield the following interesting conclusions:

- The sensor system reliability numbers generally fall within the same range of Case 1. The higher closing speed is compensated by better sensor range due to less weather effect.
- Weather is not a primary driver at 30K feet altitude. This would explain most of the trending differences between this case and Case 1. For example, there is little reliability improvement by adding a KAMS to 2 MIDAS's (i.e., from configuration #2 to #3). Same phenomenon can be seen from configuration #5 to #6 and from configuration #6 to #7.

- For forward sector only, there is, as expected, little benefit to add from 2 to 6 MIDAS's to get a 4-pi FOV (i.e., from configuration #2 to #4). However, this would not be the case for all aspect success criteria.

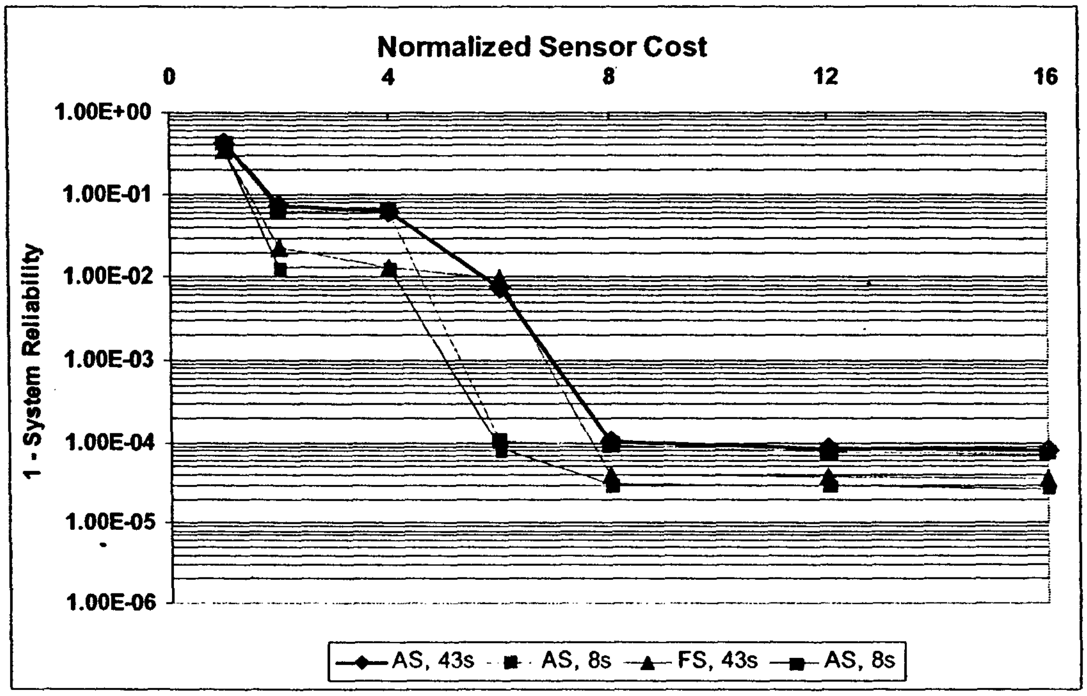


Figure 9. Case 2 - Sensor System Reliability versus Normalized Sensor Cost

VI. SUMMARY

The FOV and TTG coverage modeling tools developed by Northrop Grumman under the AFRL-funded AFCST program enabled a fairly detailed, quantitative S&A sensor system reliability analysis capability. The two study cases, a low altitude landing and a high altitude cruise condition, were used along with seven different passive MIDAS and active KAMS configurations. The matrix of reliability analysis results provided valuable insight into S&A sensor cost versus benefit trades. Critical environmental parameters like weather, intruder size, speed, and collision geometry were identified and their effects on sensor system performance well understood. This knowledge gained would be extremely valuable for specifying and tailoring S&A requirements for operating UAVs safely in FAA-controlled airspace and military theaters.

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